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TECHNICAL MEMORANDUM

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ANALYTICAL INVESTIGATION OF THE SPIN AND RECOVERY CHARACTERISTICS OF A SUPERSONIC TRAINER AIRPLANE HAVING A 24° SWEPT WING

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SUMMARY

An analytical study has been made to aid in predicting the spin entry, developed spin, and recovery characteristics of a supersonic trainer airplane having a 24° swept wing. Computations, which simulated conditions for which the airplane obtained a disturbance that put it at a high angle of attack with applied rotation, were made to determine (1) if a developed spin is possible and (2) the optimum control manipulations for recovery from such a spin. After it was found that a developed spin was possible, attempts were then made to simulate entry to the spin by more normal procedures, such as flying the airplane through the stall angle of attack. This approach was used for both erect and inverted conditions of the airplane.

As the analytical study progressed, the results were applied in conducting airplane spin flight tests. The study indicated that the airplane is not prone to enter an erect spin from normal flight conditions, but that developed erect spins are possible and may be either oscillatory or smooth and flat. The airplane is capable of recovering from the oscillatory spin but will not satisfactorily recover from the smooth flat spin. Therefore, the pilot must initiate optimum recovery controls, which are rudder full against the spin, ailerons three-fourths to full with the spin (stick right when spinning to the pilot's right), and as much back stick as possible, during the incipient or oscillatory spins in order to achieve recovery to controlled flight.

Indications are that the positive pitching velocity is the major factor that allows entering an erect spin; therefore, keeping the pitching velocity as small as possible when the airplane is progressing to positive angles of attack from an inverted attitude or when the airplane is making pull-ups is highly recommended for preventing the attainment of a developed erect spin. The airplane will not spin inverted.

SYMBOLS

The body system of axes is used. This system of axes, related angles, and positive directions of corresponding forces and moments are illustrated in figure 1.

b	wing span, ft
C_l	rolling-moment coefficient, $\dfrac{M_X}{\frac{1}{2}\rho V_R^2 Sb}$
C_m	pitching-moment coefficient, $\dfrac{M_Y}{\frac{1}{2}\rho V_R^2 S\bar{c}}$
C_n	yawing-moment coefficient, $\dfrac{M_Z}{\frac{1}{2}\rho V_R^2 Sb}$
C_X	longitudinal-force coefficient, $\dfrac{F_X}{\frac{1}{2}\rho V_R^2 S}$
C_Y	side-force coefficient, $\dfrac{F_Y}{\frac{1}{2}\rho V_R^2 S}$
C_Z	normal-force coefficient, $\dfrac{F_Z}{\frac{1}{2}\rho V_R^2 S}$
$\bar{c}$	mean aerodynamic chord, ft
F_X	longitudinal force acting along X body axis, lb
F_Y	side force acting along Y body axis, lb
F_Z	normal force acting along Z body axis, lb
g	acceleration due to gravity, 32.17 ft/sec^2
h	altitude, ft
h_1	altitude at beginning of time increment, ft
h_2	altitude at end of time increment, ft

δ_r rudder deflection with respect to fin, positive with trailing edge to left, deg

θ_{Eu} total angular movement of X body axis from horizontal plane measured in vertical plane, positive when airplane nose is above horizontal plane, deg

ρ air density, slugs/cu ft

ϕ angle between Y body axis and horizontal measured in vertical plane, positive for erect spins when right wing downward and for inverted spins when left wing downward, deg

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ϕ_{Eu} total angular movement of Y body axis from horizontal plane measured in YZ body plane, positive when clockwise as viewed from rear of airplane (if X body axis is vertical, ϕ_{Eu} is measured from a reference position in horizontal plane), deg

ψ_{Eu} horizontal component of total angular deflection of X body axis from reference position in horizontal plane, positive when clockwise as viewed from vertically above airplane, deg

$$C_{l_p} = \frac{\partial C_l}{\partial\left(\frac{pb}{2V_R}\right)}$$

$$C_{m_q} = \frac{\partial C_m}{\partial\left(\frac{q\bar{c}}{2V_R}\right)}$$

$$C_{n_r} = \frac{\partial C_n}{\partial\left(\frac{rb}{2V_R}\right)}$$

$$C_{l_\beta} = \frac{\partial C_l}{\partial \beta}$$

$$C_{n_\beta} = \frac{\partial C_n}{\partial \beta}$$

$$C_{Y_\beta} = \frac{\partial C_Y}{\partial \beta}$$

tunnel with small dynamic models, ref. 4), were made to determine (1) if a developed spin is possible and (2) the optimum control manipulations for recovery from such a spin. After it was found that a developed spin was possible, attempts were then made to enter this spin by more normal procedures, such as flying the airplane through the stall angle of attack. This approach was used for both erect and inverted conditions of the airplane. In addition, calculations were made in which an erect developed spin was obtained when the airplane started from an inverted attitude.

It should be mentioned that the pitching moments measured by Norair and Ames differed over part of the angle-of-attack range (30° to 70°), and the effect of this difference was evaluated during this study. In investigating the various techniques for entering the spin from below the stall angle of attack, both sets of pitching-moment data were used because the airplane had to go through the questionable angle-of-attack range (30° to 70°). However, when calculations were made simulating conditions for which the airplane obtained a disturbance that put it at a high angle of attack with applied rotation, the Ames pitching-moment data were arbitrarily used since the two sets of data agree for angles of attack above 70°.

The inputs simulating airplane control movements were introduced into the computer by means of appropriate switches. The timing and direction of these inputs were based on the time histories of the computed motion as observed from the computer print-out tables. The significance of motions calculated after application of controls for attempted recoveries was evaluated on the basis of the following considerations: A spin is considered terminated when either the spin rotation ceases, even though the angle of attack may still be greater than the stall angle ($\alpha \approx 15^\circ$), or the angle of attack becomes and remains less than the stall angle. Usually, when the angle of attack becomes less than the stall angle, the airplane enters a steep dive without rotation ($r = 0$). In some cases, however, the airplane may be turning or rolling in a spiral glide or an aileron roll. Also, sometimes the airplane may roll or pitch to an inverted attitude from the erect spin and may still have some rotation, but it is out of the original erect spin.

On the supersonic trainer airplane used in the spin demonstration flights, it was impossible to obtain both full back stick and full aileron deflection with the seat raised above the full-down position because of interference with the pilot's legs, and this factor was considered in the present analytical study. Generally, either full deflection of the all-movable horizontal tail and one-half ailerons or zero deflection of the all-movable horizontal tail and full ailerons was used. Also, it was understood that the production trainer airplane would have available only $\pm 6^\circ$ of rudder deflection, whereas the spin

A second calculation was made wherein neutral elevator, full left ailerons (stick full left), and 6° of right rudder were used to maintain the spin. The resulting motion indicates a relatively steady spin in which the airplane was at an angle of attack of approximately 68°, had very small oscillations in roll, and had a rotation rate of about 1.9 radians/sec. A recovery from this spin was attempted by reversing the ailerons to full with the spin (right stick) and the rudder to against the spin (6° left); recovery was satisfactory, being obtained in approximately two turns. (See fig. 9.) Three-fourths aileron deflection with the spin and 6° of left rudder were also used in an attempt to recover from the spin shown in figure 9. The results are presented in figure 10 and indicate that a recovery was achieved in approximately two and one-half spinning turns.

From these time histories (figs. 8, 9, and 10), it might be concluded that the airplane will maintain a spin if a condition simulating a launch into a spin at a high angle of attack is obtained and that the airplane will recover from the spin satisfactorily if three-fourths to full ailerons with the spin and 6° of rudder against the spin are applied (right stick and left rudder when spinning to the pilot's right). In addition, as much back stick as possible should be applied to help slow the rotation rate.

Effects of altitude on spins and recoveries.- The time histories in figures 8 and 9, as noted previously, were calculated with the air density held constant simulating an altitude of 30,000 feet. In an attempt to compute the altitude effects on the developed spin and recovery characteristics, the inputs used in computing the time histories in figures 8 and 9 were again used with the air density held constant simulating an altitude of 45,000 feet. The resulting motions corresponding to those of figures 8 and 9 are presented on figures 11 and 12, respectively, and indicate that the spinning motions and recoveries at 45,000 feet were similar to those at 30,000 feet.

Attempted spin entries from zoom maneuver.- Attempts were made to calculate a spin entry by simulating the flying of the airplane up through the stall angle of attack while in a nose-high attitude (zoom maneuver). These calculations were made simulating an altitude of 30,000 feet for instances where full ailerons, one-half ailerons, 6° and 30° rudder, and combinations thereof were used in attempts to attain a developed erect spin. Both the Ames and Norair pitching-moment data were used as inputs to evaluate the effect of the magnitude of C_m in the angle-of-attack range from 30° to 70°. Full back stick was used in each case to stall the airplane. Spins could not be obtained for any of these conditions. A typical time history is presented as figure 13 and shows that the angle of attack got no higher than approximately 30° and that the rate of rotation was, in general, less than 0.2 radian/sec.

history using the Norair data is presented in figure 14; the time history using the Ames data is presented in figure 15.

From the last two calculations, indications are that the differences in the angular velocities acquired as the airplane rolled erect determined whether the airplane would enter an erect spin starting from an inverted attitude. It is reasoned that the difference in the control manipulations in the calculated result and those in the experimental result caused the differences in angular velocities. In order to determine which of the angular velocities it was that allowed the airplane to progress to positive angles of attack and into an erect developed spin, additional calculations were made and indicated that the pitching velocity q was the factor that allowed the erect spin to develop. Therefore, keeping q as small as possible when the airplane is progressing to positive angles of attack is highly recommended for preventing the attainment of a developed erect spin. It is believed that the most likely way to keep q small (near zero), when the craft is progressing towards positive angles of attack, is for the pilot to neutralize the rudder, utilize the ailerons to keep the wings level, and push the stick full forward to help keep the nose down.

Application of analytical results to flight tests.- By utilizing the results of the analytical study that indicated the pitching velocity q to be the factor which allowed the original erect spin to be obtained, further flight tests of the airplane were made. These tests showed that when a pitching velocity of sufficient magnitude was achieved, an erect spin could be readily obtained on the airplane; not only could this be done when starting from an inverted attitude and rolling to an erect attitude but also when starting from an erect attitude and making an abrupt pull-up. (When a spin was entered starting from erect attitudes, the elevator had to be deflected at maximum rates in order to obtain the required pitching velocity.) As stated previously, two types of spins were encountered during spin flight tests made after the problem of the spin-entry technique was solved. One type of spin was oscillatory and recoveries from these spins were readily obtainable. The second type of spin had a faster yaw rate and was less oscillatory, and no recovery could be achieved with use of the available controls. When this latter spin was obtained, recovery in each instance required use of a spin-recovery parachute. It was obvious from these flight tests results that the pilot must concern himself with initiating recovery from the incipient and oscillatory spins and not let a flat smooth spin develop.

Simulation of the smooth flat spin.- Several calculations were made in an attempt to simulate the smooth flat spin obtained by the airplane (from which recovery was not obtainable) to determine if the analytical technique would also indicate no recoveries. The pitching moments obtained by both Norair and Ames were used in this portion of the analytical study. First, the time history shown in figure 14, which had was indicated to be possible by applying optimum controls, which are rudder full against the spin, ailerons three-fourths to full with the spin (stick right when spinning to the pilot's right), and as much back stick as possible. It was indicated that satisfactory recovery would not be obtained from the smooth flat spin, even when optimum recovery controls are utilized.

Calculations for Inverted Spins

Calculations were made to determine if an inverted spin could be maintained if the airplane is launched at a high angle of attack with rotation applied. A number of calculations were made to determine if a developed inverted spin could be maintained. For the first group of calculations, the initial conditions shown in table II, column D, were used, and three representative time histories are presented in figures 16, 17, and 18. The motion shown in figure 16 was obtained by using aerodynamic data measured in the Norair 7- by 10-foot wind tunnel. The calculations simulated 30° of prospin rudder deflection (left rudder when yawing to the pilot's left), $+8^{\circ}$ of elevator deflection (stick forward; trailing edge of horizontal tail is up with respect to the earth because of craft being in inverted attitude), and zero aileron deflection. The result of these calculations is considered to be no spin since the airplane rolled erect in less than one spinning turn. This result might have been expected, however, since the airplane in its inverted attitude has negative effective dihedral and experience has indicated that positive effective dihedral is helpful, if not necessary, in entering and maintaining spins. Another calculation was made by using the same inputs except that positive effective dihedral (positive values of C_{l_β} in the inverted attitude) was arbitrarily used. (See fig. 19 for values of C_{l_β} used.) The resulting time history is presented as figure 17 and indicates that an inverted spin could now be maintained. When the rudder deflection was decreased to 6° for this latter condition, no inverted spin could be maintained. (See fig. 18.) This result is probably due to the relatively small prospin incremental yawing moment produced by the rudder when deflected only 6°. (Compare $\Delta C_{n,r}$ for $\delta_r = -6^{\circ}$ with $\Delta C_{n,r}$ for $\delta_r = -30^{\circ}$ in fig. 5.)

A number of other calculations were made for which more rapid initial rotational rates were applied and the measured values of C_{l_β} were used. These calculations were made for both ailerons neutral and ailerons against the inverted spin, and no spins were obtained in all calculations as long as the small negative measured values of C_{l_β} were used.

1. The airplane is not prone to enter an erect developed spin from normal flight conditions. However, it is possible under some circumstances for the airplane to spin erect, and the resulting spin may be either oscillatory, or smooth and flat. Both the analytical and the flight test results indicate that the airplane is capable of recovering from the oscillatory spin and will not satisfactorily recover from the smooth flat spin. Therefore, the pilot must initiate optimum recovery controls, which are rudder full against the spin, ailerons three-fourths to full with the spin (stick right when spinning to the pilot's right), and as much back stick as possible, during the incipient or oscillatory spins in order to achieve recovery to controlled flight. An inverted developed spin is not possible. Any inverted poststall gyrations obtained can be terminated by neutralizing all controls.

2. Indications are that the positive pitching velocity is the major factor that allows entering an erect spin; therefore, keeping the pitching velocity as small as possible when the airplane is progressing to positive angles of attack from an inverted attitude or when the airplane is making pull-ups is highly recommended for preventing the attainment of a developed erect spin. It is believed that the most likely way to keep the pitching velocity small (near zero), when the airplane is progressing towards positive angles of attack from an inverted attitude, is for the pilot to neutralize the rudder, utilize the ailerons to keep the wings level, and push the stick full forward to help keep the nose down.

3. A comparison of the results of full-scale flight tests with results obtained analytically indicates that the calculated results are in good qualitative agreement with those obtained on the spin demonstration airplane.

4. Analytical studies such as the one presented in this paper can be used to expedite spin demonstration flight tests of full-scale airplanes.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., August 23, 1961.

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$$V_R = \sqrt{u^2 + v^2 + w^2}$$

$$V = -u \sin \theta_{Eu} + v \cos \theta_{Eu} \sin \phi_{Eu} + w \cos \theta_{Eu} \cos \phi_{Eu}$$

$$h_2 = h_1 - \Delta t\ V$$

$$\dot{\theta}_{Eu} = q \cos \phi_{Eu} - r \sin \phi_{Eu}$$

$$\dot{\phi}_{Eu} = p + r \tan \theta_{Eu} \cos \phi_{Eu} + q \tan \theta_{Eu} \sin \phi_{Eu}$$

$$\dot{\psi}_{Eu} = \frac{\dot{\phi}_{Eu} - p}{\sin \theta_{Eu}}$$

$$\text{Turns in spin} = \frac{\int \dot{\psi}_{Eu}\ dt}{2\pi}$$

$$\phi_{Eu} = \sin^{-1} \frac{\sin \phi}{\cos \theta_{Eu}}$$

TABLE I

MASS AND DIMENSIONAL CHARACTERISTICS OF THE

SUPERSONIC TRAINER AIRPLANE

$\bar{c}$, ft	7.73
b, ft	25.25
S, sq ft	170.00
W, lb	10,040.00
Center-of-gravity location, percent $\bar{c}$	25.00
I_X, slug-ft^2	1,700
I_Y, slug-ft^2	29,500
I_Z, slug-ft^2	30,100
Maximum control deflections:	
All-movable horizontal tail, deg	T.E. down 8 T.E. up 17
Rudder, deg	±6 or ±30
Aileron, deg	T.E. down 25 T.E. up 35

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TABLE II

VALUES OF SOME PERTINENT VARIABLES AT ZERO TIME IN CALCULATIONS

	Column A	Column B	Column C	Column D
α, deg	68	5	5	-70
θ_{Eu}, deg	-22	-61	-61	-26
ϕ_{Eu}, deg	-2	80	80	195
β, deg	-4	35	35	5
p, radians/sec	0.68	-1.60	-0.20	0.58
q, radians/sec	-0.06	0.30	1.04	0
r, radians/sec	1.65	0.30	0.46	-1.33

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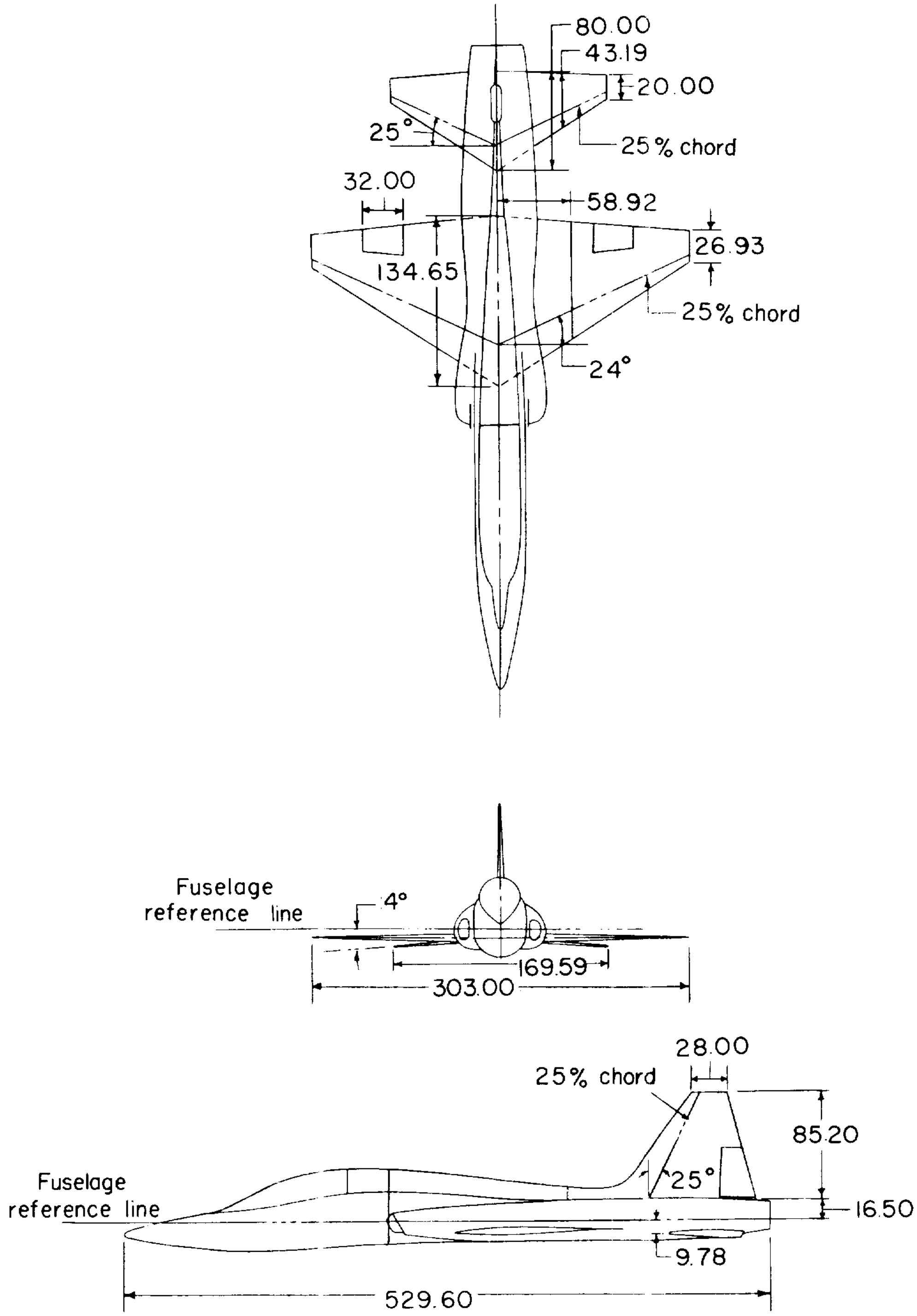

Figure 2.- Three-view drawing of supersonic trainer airplane. (All dimensions are in inches.)

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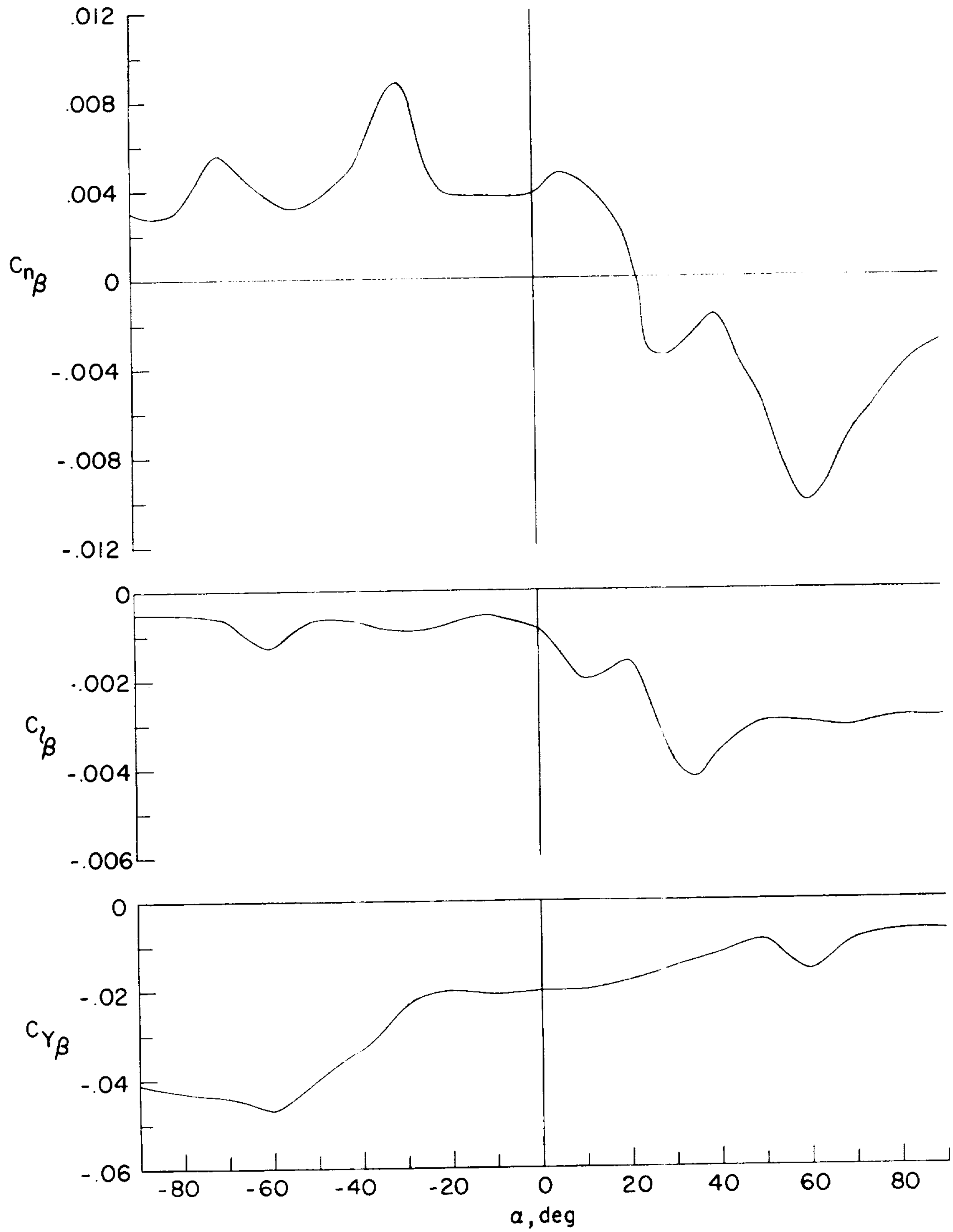

Figure 4.- Variations of sideslip derivatives with angle of attack.

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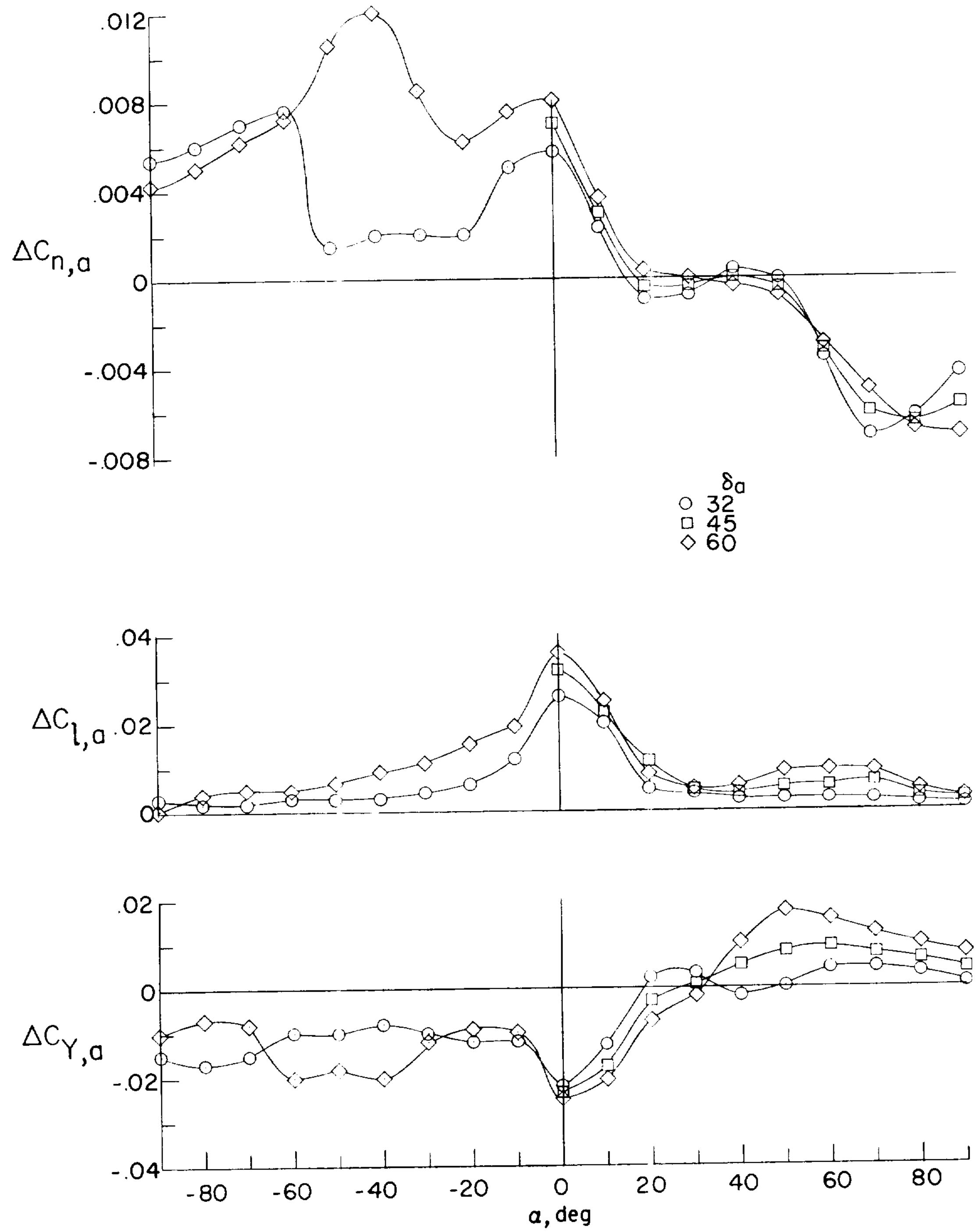

Figure 6.- Variations in increments in moment and side-force coefficients due to deflecting ailerons.

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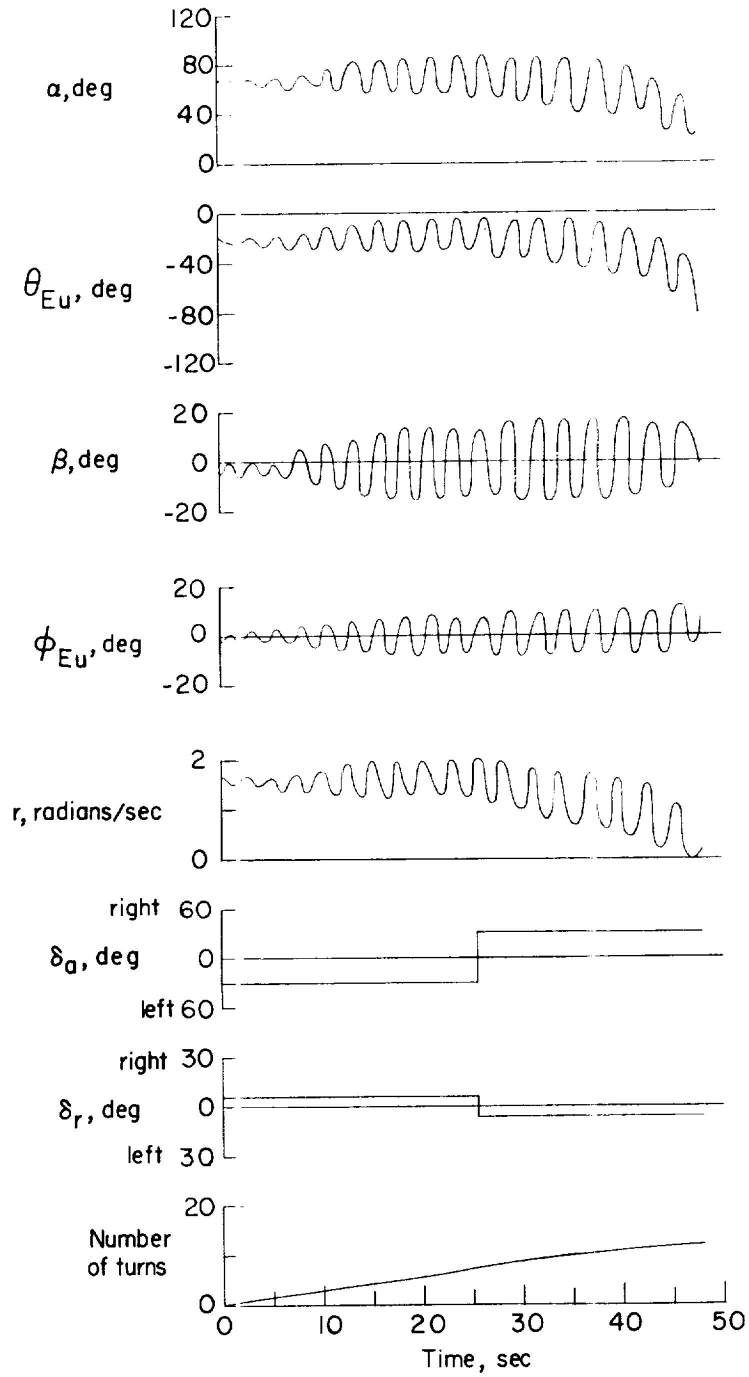

Figure 8.- Calculation simulating spin-tunnel launching technique. Elevator full up; 6° rudder and one-half aileron deflections; h = 30,000 feet.

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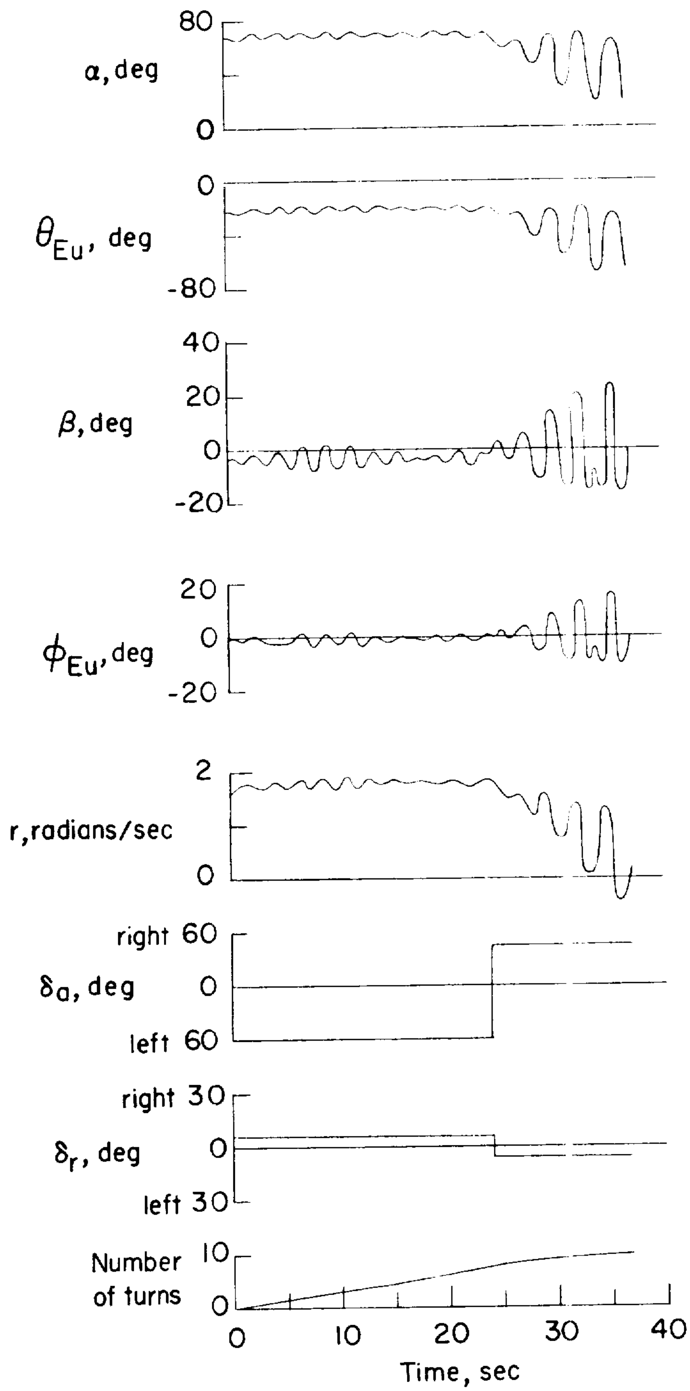

Figure 10.- Calculation in simulating a recovery from the spinning motion presented in figure 9. Elevator neutral; 6° rudder and three-fourths aileron deflections; h = 30,000 feet.

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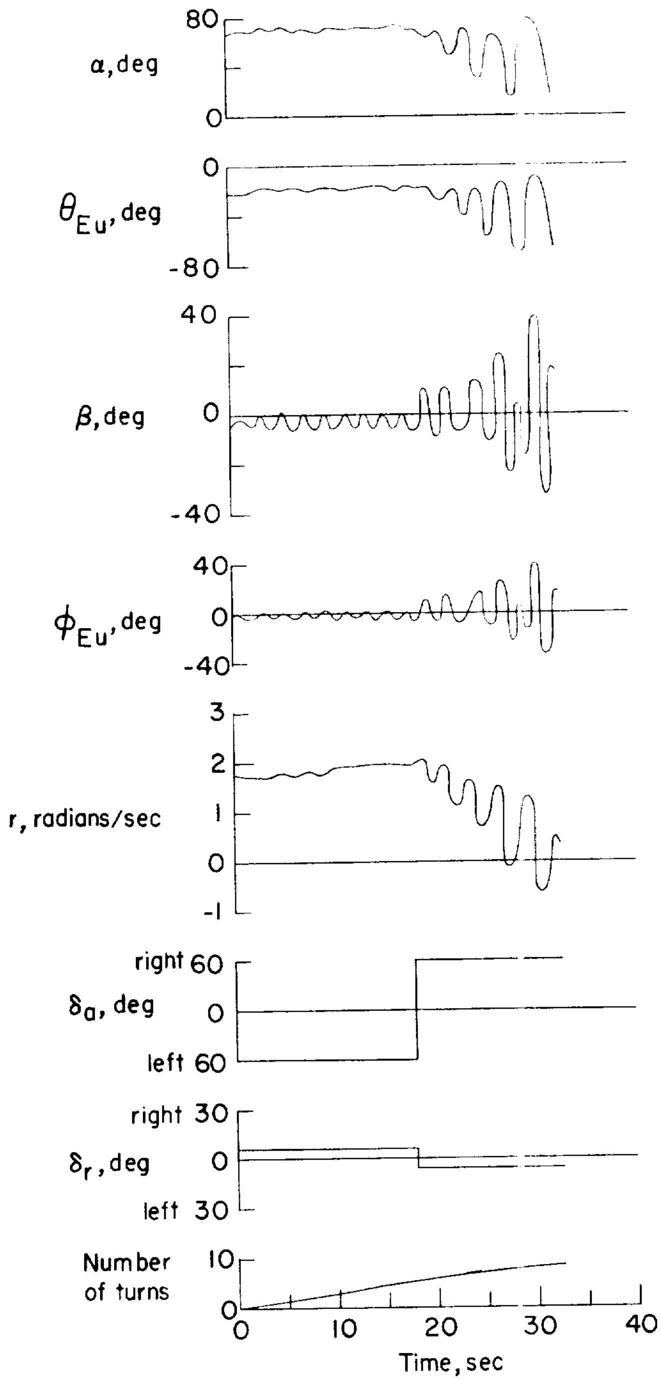

Figure 12.- Calculation simulating spin-tunnel launching technique. Elevator neutral; 6° rudder and full-aileron deflections; h = 45,000 feet.

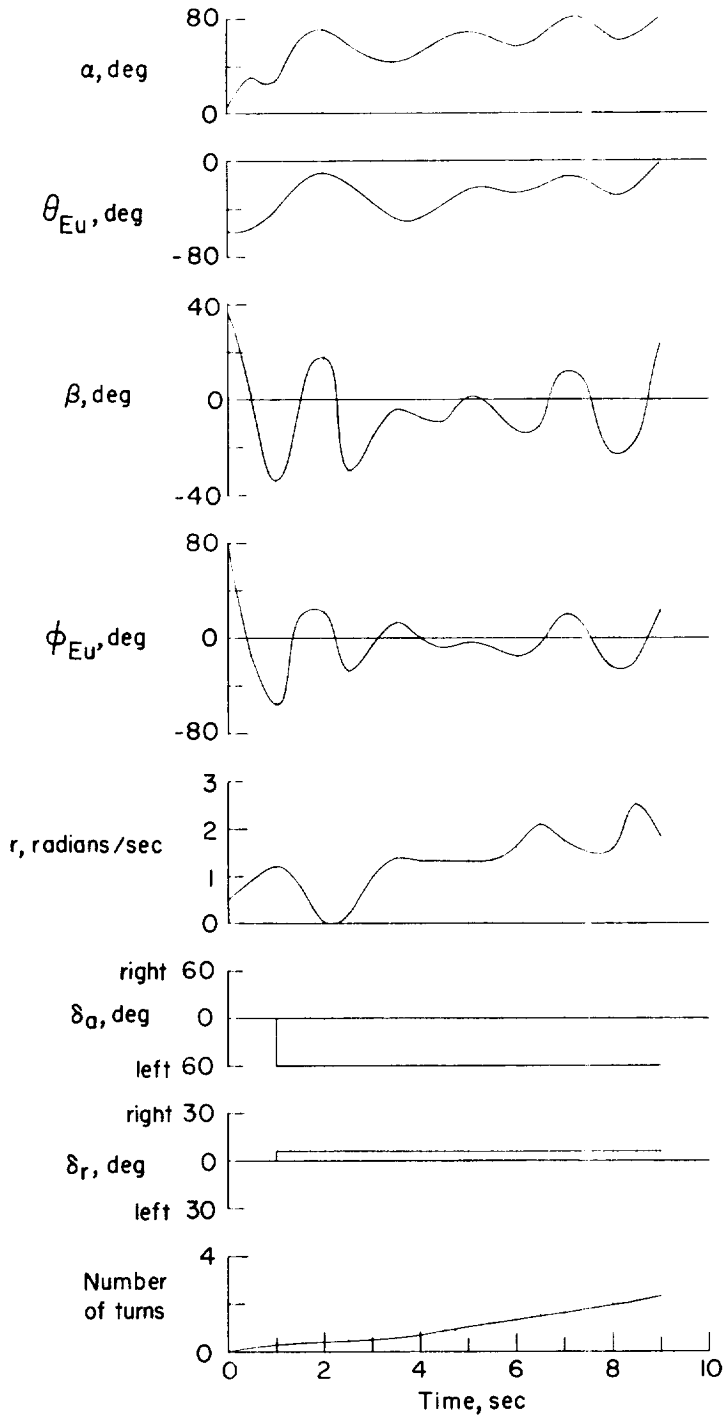

Figure 14.- Calculation simulating erect spin entry by using initial conditions listed in column C, table II and Norair pitching-moment curve (0° elevator).

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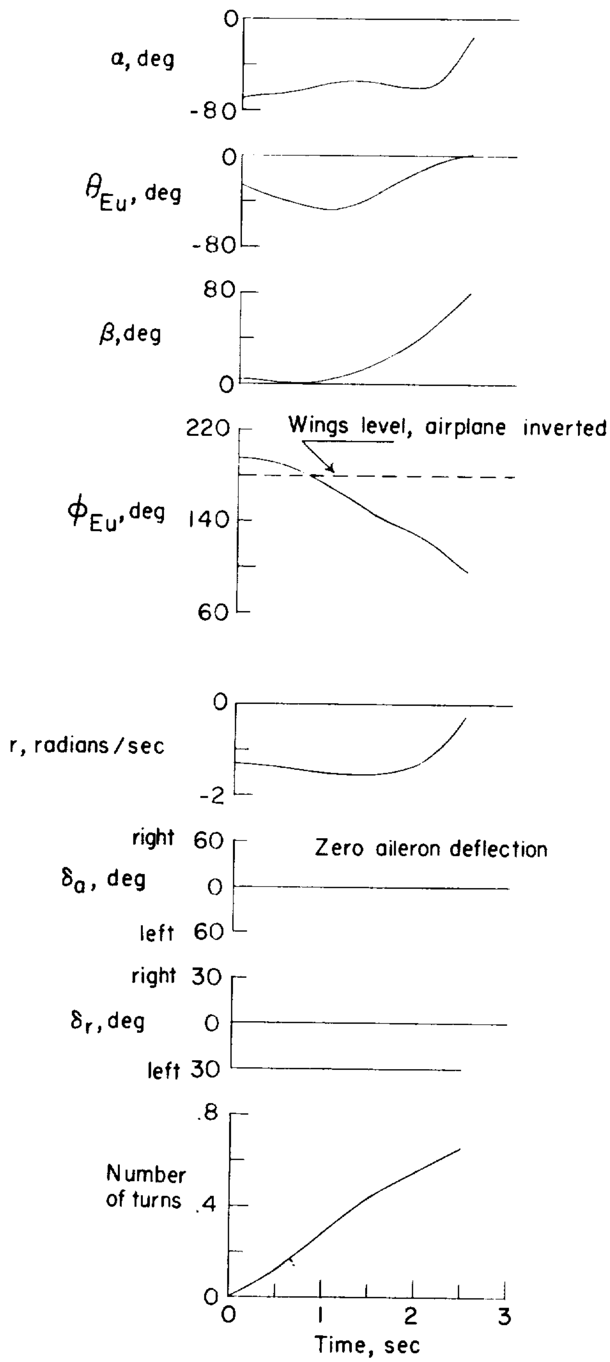

Figure 16.- Calculation simulating spin-tunnel launching technique with craft inverted. 8° elevator, 30° rudder, and zero aileron deflections.

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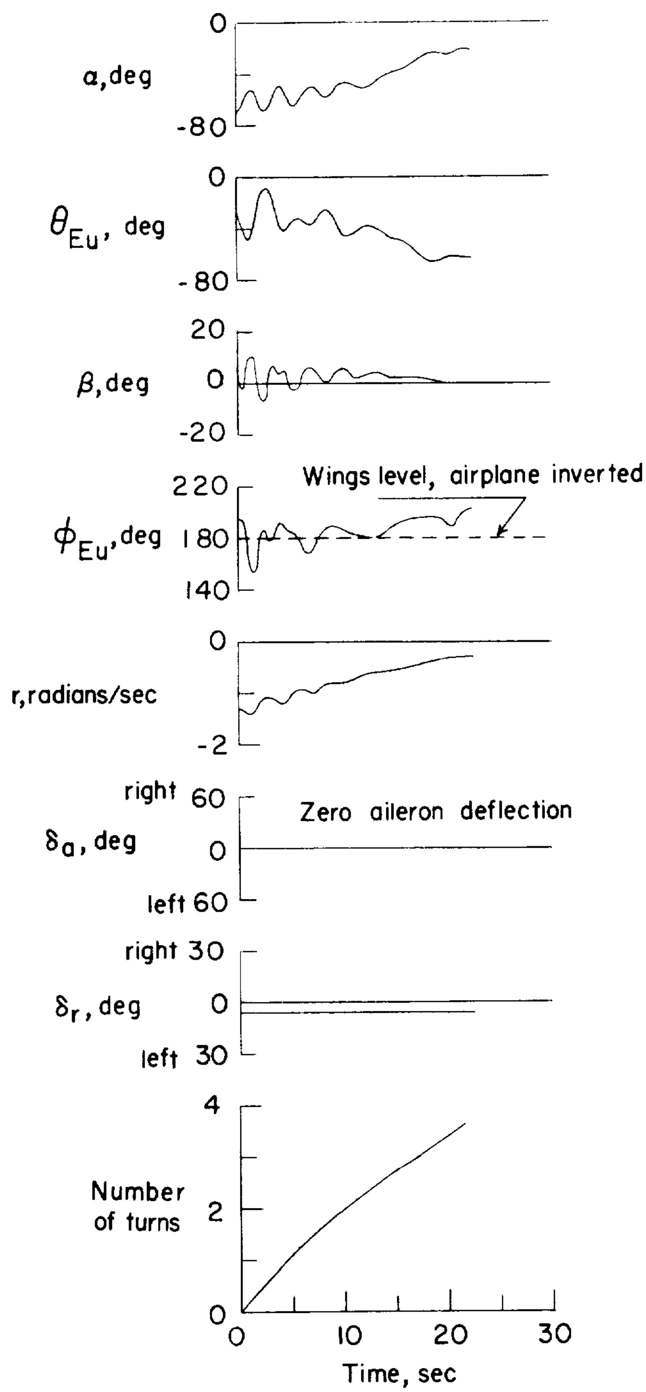

Figure 18.- Calculations simulating spin-tunnel launching technique with craft inverted. 8° elevator, 6° rudder, and zero aileron deflections. (Large positive values of $C_{l_{\beta}}$ arbitrarily used.)